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(71) Applicant: TOYOTA JIDOSHA KABUSHIKI KAISHA
Aichi-ken 471-8571 (JP)

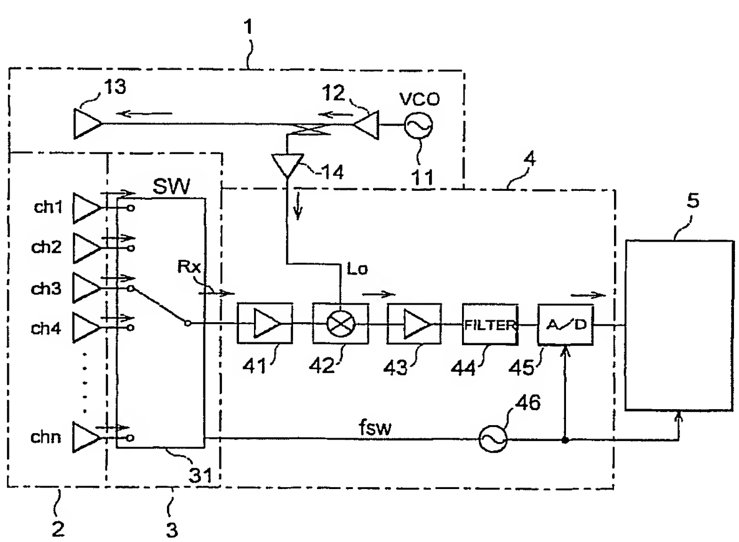
(72) Inventor: Kawakubo, Atsushi
Toyota-shi, Aichi-ken, 471-8571 (JP)

(74) Representative:
Ben-Nathan, Laurence Albert et al
Urquhart-Dykes & Lord
91 Wimpole Street
London W1M 8AH (GB)

(54) Radar apparatus

(57) An object is to provide a cheap digital beamforming radar apparatus. For achieving it, the radar apparatus of the present invention comprises a transmit section for radiating a transmit signal in the form of an electromagnetic wave, an array antenna comprised of a plurality of antenna elements for receiving an electromagnetic wave re-radiated from an object when the electromagnetic wave of the transmit signal reaches the object, as a receive signal, a switching device for connecting either one of the antenna elements to a predetermined terminal in an alternative way by a switching signal, a receive section for downconverting the receive signal obtained from the predetermined terminal by use of part of the transmit signal to generate a difference signal between the transmit signal and the receive signal and converting this difference signal to a digital signal, and a digital signal processing section for subjecting the digital signal from the receive section to a predetermined process to detect a distance to the object or a relative velocity of the object.

Fig.1



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art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]

Fig. 1 is a structural diagram to show the radar apparatus of an embodiment of the present invention;
Fig. 2A and Fig. 2B are graphs for explaining the principle of detection by FM-CW radar;
Fig. 3A and Fig. 3B are graphs for explaining the principle of detection by FM-CW radar;
Fig. 4 is a diagram for explaining the principle of a phased array antenna;
Fig. 5 is a diagram for explaining the principle of a digital beamforming (DBF) antenna;
Fig. 6 is a graph to show signals downconverted in the first embodiment;
Fig. 7 is a graph to show the signal of the first channel extracted from Fig. 6;
Fig. 8 is a flowchart to show the overall operation of the first embodiment;
Fig. 9 is a structural diagram to show the radar apparatus of the second embodiment of the present invention;
Fig. 10 is a timing chart to show the switching operation of switch 6;
Fig. 11 is a timing chart to show output signals from mixer 42;
Fig. 12 is a timing chart to show output signals from second mixer 72; and
Fig. 13 is a spectral map to show the way of frequency conversion.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0011] Fig. 1 is a structural diagram to show the radar apparatus which is as an embodiment of the present invention. This radar apparatus is an FM-CW radar apparatus using a transmit signal resulting from frequency modulation (FM) of continuous wave (CW) and is also DBF radar apparatus to perform the digital beamforming process.

[0012] The principle of detection by the FM-CW radar and the fundamental concept of the DBF technology will be described prior to description of specific structure and operation of the present embodiment.

[0013] First, the principle of detection by the FM-CW radar will be described referring to the graphs of Figs. 2A and 2B and Figs. 3A and 3B. Fig. 2A is a graph to show change in transmit frequency, and change in receive frequency of re-radiated beam from a target located at a position the distance R apart and moving at the relative velocity of zero, wherein the ordinate indicates the frequency and the abscissa the time. The solid line indicates the frequency of transmit signal and the dashed line the frequency of receive signal. As apparent from this graph, the transmit signal is a modulated signal resulting from triangular frequency modulation of continuous wave. The center frequency of the modulated wave is f0, the frequency shift width ΔF, and the repetition frequency of the triangular wave fm. Fig. 3A is a graph to indicate change in receive signal when the relative velocity of the target is not zero but velocity V, wherein the solid line represents the frequency of transmit signal and the dashed line the frequency of receive signal. The definition of the transmit signal and coordinate axes is the same as in Fig. 2A.

[0014] It is understood from Fig. 2A and Fig. 3A that the receive signal under radiation of such transmit signal experiences a time delay T (T = 2R/C: C is the speed of light) according to the range R when the relative velocity of the target is zero and that the receive signal experiences the time delay T according to the range R, and a frequency shift D commensurate with the relative velocity when the relative velocity of the target is V. The example shown in Fig. 3A indicates the case where the frequency of the receive signal is shifted up in the same graph and thus the target is approaching.

[0015] When this receive signal is mixed with part of the transmit signal, a beat signal will be obtained. Fig. 2B and Fig. 3B are graphs to show the beat frequency when the relative velocity V of the target is zero and when the relative velocity V is not zero, respectively, wherein the time axis (abscissa) is timed with that of Fig. 2A or Fig. 3A, respectively.

[0016] Now, let fr be the beat frequency at the relative velocity of zero, fd be the Doppler frequency based on the relative velocity, fb1 be the beat frequency in frequency-increasing intervals (up intervals), and fb2 be the beat frequency in frequency-decreasing intervals (down intervals). Then the following equations hold.

$$fb1 = fr - fd \tag{1}$$

$$fb2 = fr + fd \tag{2}$$

[0017] Hence, fr and fd can be calculated from the following equations (3) and (4) by separately measuring the beat frequencies fb1 and fb2 in the up interval and in the down interval, respectively, of the modulation cycles.

$$fr = (fb1 + fb2)/2 \tag{3}$$

$$fd = (fb2 - fb1)/2 \tag{4}$$

[0018] Once fr and fd are obtained, the range R and the relative velocity V of the target can be calculated from the following equations (5) and (6).

tenna 2 is connected to an associated input terminal. The output terminal is arranged to be connected to either one of the input terminals and the connection is switched at regular intervals by switching signal (clock signal). The switching of connection is electrically conducted on the circuitry.

[0031] The receive section 4 is provided with RF amplifier 41, mixer 42, amplifier 43, filter 44, A/D converter 45, and switching signal oscillator 46. A signal outputted from the output terminal of the switch 3, which is a signal received by either antenna element of the array antenna 2, is amplified by the RF amplifier 41 and the amplified signal is mixed with part of the transmit signal from the RF amplifier 14 in the mixer 42. This mixing causes the receive signal to be downconverted, thereby creating a beat signal which is a difference signal between the transmit signal and the receive signal. The beat signal is input through the amplifier 43 and low-pass filter 44 into the A/D converter 45 to be converted to a digital signal at the timing of an output signal from the oscillator 46, i.e., at the timing of the clock signal for switching of connection in the switch 3.

[0032] The digital signal processing section 5 carries out the digital beamforming (DBF) based on the aforementioned principle with the input of the digital beat signal from the A/D converter 45.

[0033] Next described is the overall operation of the radar apparatus constructed as described above.

[0034] Let f_{TX} be the frequency of the transmit signal, $f_{RX}(i)$ be the frequency of the receive signal (where i = 1, 2,..., n), and fb(i) be the frequency of the beat signal (where i = 1, 2,..., n). Then the frequency fb(i) of the beat signal is expressed by the following equation.

$$fb(i) = |f_{TX} - f_{RX}(i)| \qquad (7)$$

[0035] With an example of the radar apparatus to be mounted on automobiles, $f_{TX} \fallingdotseq f_{RX}(i) \fallingdotseq 60$ GHz and then fb(i) < 100 kHz, approximately. When in this example the frequency fsw of the clock signal, which is the switching signal of the switch 3, is set to several MHz to several hundred MHz, the mixer 42 downconverts several hundred to several thousand cycles of each receive wave (in the 60 GHz band) from the respective channels (antenna elements) to repetitively generate beat signals of fb(i) from 1 to n in order.

[0036] The downconverted signals are illustrated in Fig. 6. In this figure the number n of receive channels is set as n = 8 and the value of fsw is decreased to a value close to fb(i) for simplicity. There is a small shift between phases of the beat signals obtained in the respective antenna elements of CH1 to CH8.

[0037] In Fig. 6, eight curved lines indicated by thin lines represent the beat signals in the case where each of the signals received by the respective channels (antenna elements) of the array antenna 2 is downconverted. Since the switching of channel is conducted at the frequency fsw by the switch 3 in the present embodiment, the beat signals obtained in the mixer 42 are chopped beat signals indicated by solid lines. Each of the chopped beat signals of the individual channels is input through the amplifier 43 and filter 44 into the A/D converter 45.

[0038] Since the A/D converter 45 performs the A/D conversion in synchronism with the switching timing of the switch 3, there is 1:1 correspondence between the digital data after the A/D conversion and the channels. The timing of A/D conversion in each channel is slightly delayed from the switching timing of the switch 3, so as to be set at the center of a connection period. Fig.7 is a graph to show the signal of the first channel extracted from Fig. 6, in which positions indicated by black dots are points of A/D conversion timing.

[0039] Then the digital signal processing section 5 accumulates fixed data amounts of the serial data of the eight channels, for example, data of 1024 points for each channel, in eight buffers. Each channel and each buffer are in 1:1 correspondence. The first buffer stores 1024 chopped digital beat signals of the first channel (only three of which are illustrated in Fig. 7), and likewise, the second buffer to the eighth buffer store the digital beat signals of the second channel to the eighth channel, respectively.

[0040] In this example, the value of fsw is decreased to a value close to fb(i) for simplicity of illustration, as described above. However, fsw >> fb(i) in practice, so that the period of the switching signal is much shorter relative to the period of the beat signals than that illustrated. Therefore, the beat signals are actually chopped finer. Regeneration of fb(i) is allowed up to the frequency where the sampling theorem holds (i.e., to fsw/(2 × the number of channels)).

[0041] In the digital signal processing section 5, the data series separated in the respective channels are processed in a similar manner to those in the case of the conventional DBF radar apparatus for downconverting data for each channel. More specifically, after execution of the FFT process, the phase rotation process is carried out according to the idea of DBF as was stated referring to Fig. 4 and Fig. 5, a beam is synthesized at each direction angle, and the range to the object and the relative velocity of the object are computed according to aforementioned Eqs. (5) and (6) from frequencies of beat signals of each beam. In the last step the position and velocity of the object are determined from all these results.

[0042] Fig. 8 is a flowchart to show the whole of the sequential flow concerning the operation of the radar apparatus of the present embodiment detailed above. Let i represent a channel number and j represent a data sampling number. First, step 801 is to set i = 1 and j = 1. Then the clock signal fsw is taken in (step 802), and with detection of an edge of the clock signal the output terminal of the switch 3 is switched to the input terminal

this figure, each intermediate signal outputted from the mixer 41 is a signal amplitude-modulated by the beat signal of each channel with the intermittent signal of the frequency f_{IF} as a carrier signal. For simplifying the description, Fig. 11 shows the case where the number n of receive channels is n = 8 and fsw is decreased to a value close to fb(i), just as in the description of the first embodiment. There is also a small shift between the phases of the beat signals obtained from the respective antenna elements of CH1 to CH8.

[0059] When the intermediate signal of the frequency $f_{IF} \pm fb$ obtained in this way is amplified by the IF amplifier 71 and thereafter mixed with the intermittent signal of the frequency f_{IF} in the second mixer 72, the beat signals are obtained in succession in the sequence of the channels. Fig. 12 shows the beat signals outputted from the second mixer 72.

[0060] The processing thereafter is the same as in the first embodiment; the beat signal is input through the amplifier 43 and filter 44 to the A/D converter 45 to be subjected to A/D conversion in synchronism with the switching signal of the frequency fsw and the digital data output therefrom is supplied to the digital signal processing section 5. The processing in the digital signal processing section 5 is also similar to that in the first embodiment; the digital data input is subjected to the FFT process, thereafter the phase rotation process is effected thereon, a beam is synthesized in each direction angle, and the range to the object and the velocity of the object are computed from the frequencies of beat signals of each beam. In the final step the position and velocity of the object are determined from all these results.

[0061] Fig. 13 is a spectral map to show the way of frequency conversion in the signal processing step in the present embodiment. In the radar apparatus of the present embodiment, the receive signal 130 is replaced with signals 131 and 132 by on and off according to the intermittent signal in the switch 6, thereafter they are downconverted to the intermediate signal 133 by the mixer 42, and subsequently, it is downconverted to the beat signal 134 by the second mixer 72.

[0062] In Fig. 13, a curve 135 represents the noise floor of the mixer 42 and a curve 136 the noise floor of the second mixer 72. As apparent from this figure, the mixer 42 performs the downconverting to the IF band where the influence of the noise thereof is lowered. Then the second mixer 72, which has lower noise in the low frequency region than the mixer 42, downconverts the signal to the beat signal. Accordingly, the noise margin becomes much larger than in the homodyne method.

[0063] Since the mixer 42 has a very wide frequency band, it normally demonstrates rather much 1/f noise and FM-AM conversion noise due to the FM-CW method in the low frequency region. In contrast, the second mixer 72 has a narrower frequency band and the noise floor thereof is thus lower. The present embodiment achieves expansion of the noise margin by taking advantage of this action.

[0064] If the frequency band of the IF amplifier 71 at the front end of the second mixer 72 is made narrower, the IF signal can be separated from the FM-AM conversion noise appearing in the low frequency region, whereby the low-frequency noise can be further decreased.

[0065] The first and second embodiments described above are the radar apparatus of the FM-CW method, but the present invention can also be applied to the radar apparatus of other methods where the position and relative velocity of object are determined using the difference signal between the transmit signal and the receive signal.

[0066] As detailed above, the radar apparatus of the present invention is implemented with only one set of expensive devices necessary for downconverting, for example, such as the RF amplifier and the mixer of high frequency band, irrespective of the number of antenna elements. The entire apparatus can be constructed at low cost and in compact size accordingly.

[0067] From the invention thus described, it will be obvious that the invention may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended for inclusion within the scope of the following claims.

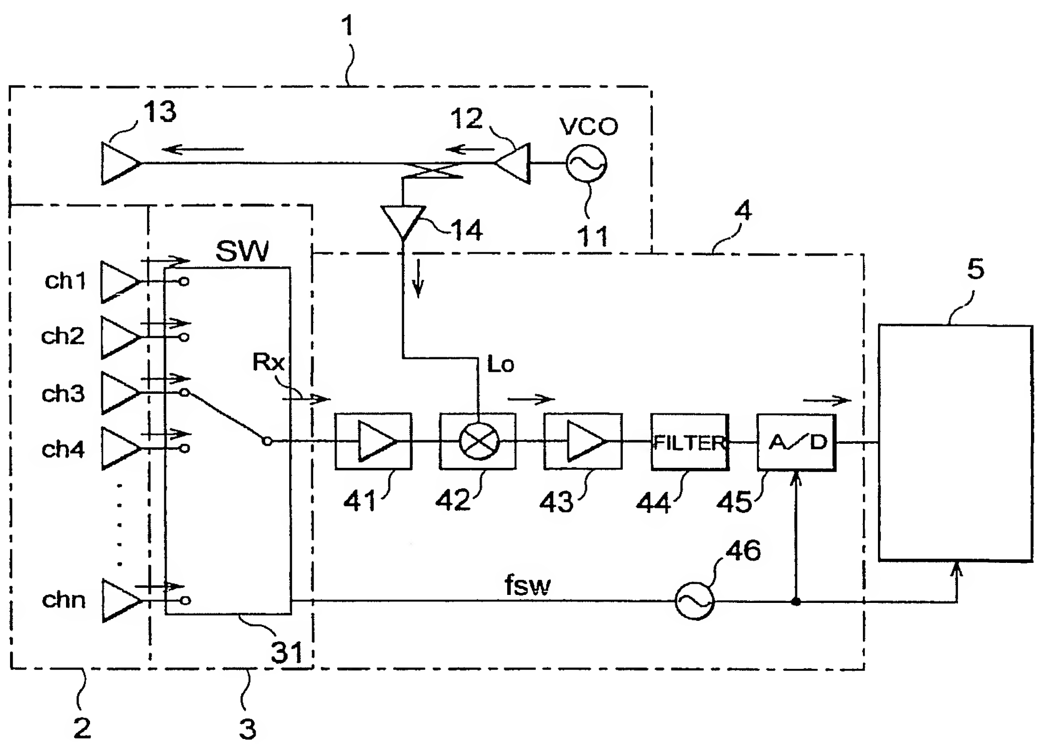
Claims

1. A radar apparatus comprising a transmit section for radiating a transmit signal in the form of an electromagnetic wave, an array antenna comprised of a plurality of antenna elements for receiving an electromagnetic wave re-radiated from an object when said electromagnetic wave of the transmit signal reaches the object, as a receive signal, switching means for connecting either one of said antenna elements to a predetermined terminal in an alternative way by a switching signal, a receive section for downconverting said receive signal obtained from said predetermined terminal by use of part of said transmit signal to generate a difference signal between said transmit signal and said receive signal and converting said difference signal to a digital signal, and a digital signal processing section for subjecting the digital signal from said receive section to a predetermined process to detect a distance to said object or a relative velocity of said object.

2. The radar apparatus according to Claim 1, wherein a frequency of said switching signal is set in a range smaller than a frequency of said transmit signal and larger than a frequency of said difference signal.

3. The radar apparatus according to Claim 2, wherein

Fig.1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13
12
VCO
11
14
4
5
SW
ch1
ch2
ch3
ch4
chn
Rx
Lo
FILTER
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43
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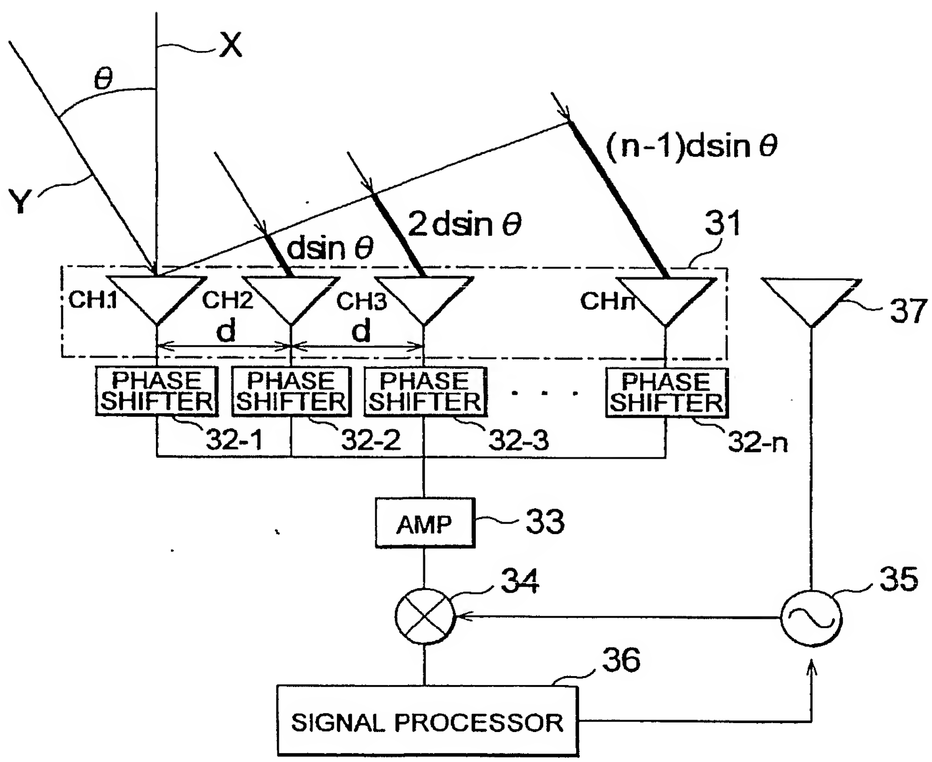
31
2
3

Fig.4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θ
Y
(n-1)dsin θ
2dsin θ
dsin θ
31
CH1
CH2
CH3
CHn
d
d
37
PHASE SHIFTER
PHASE SHIFTER
PHASE SHIFTER
PHASE SHIFTER
32-1
32-2
32-3
32-n
AMP
33
34
35
36
SIGNAL PROCESSOR

Fig.6

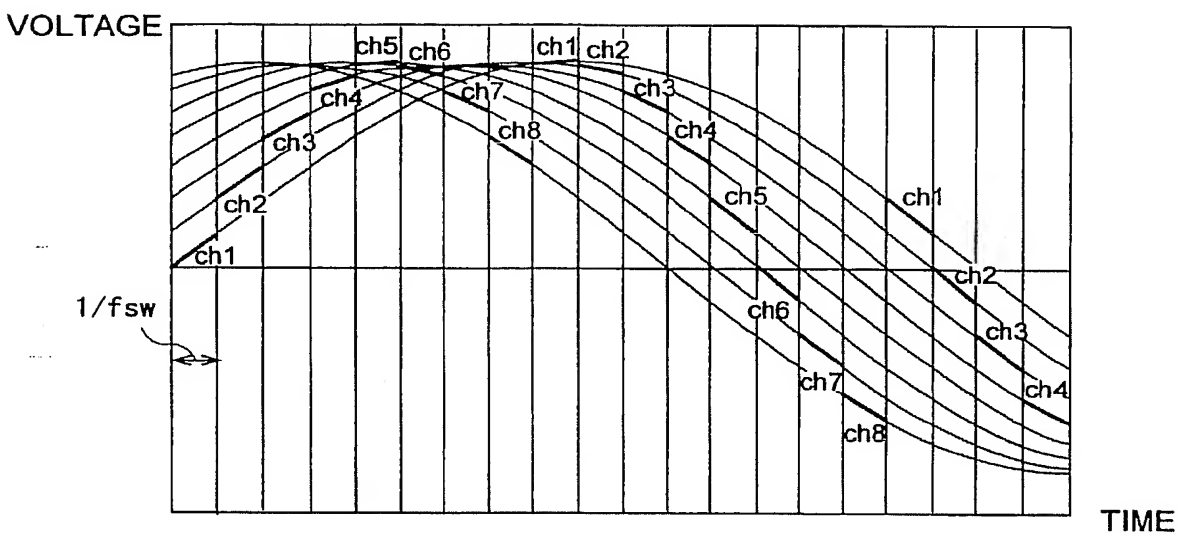
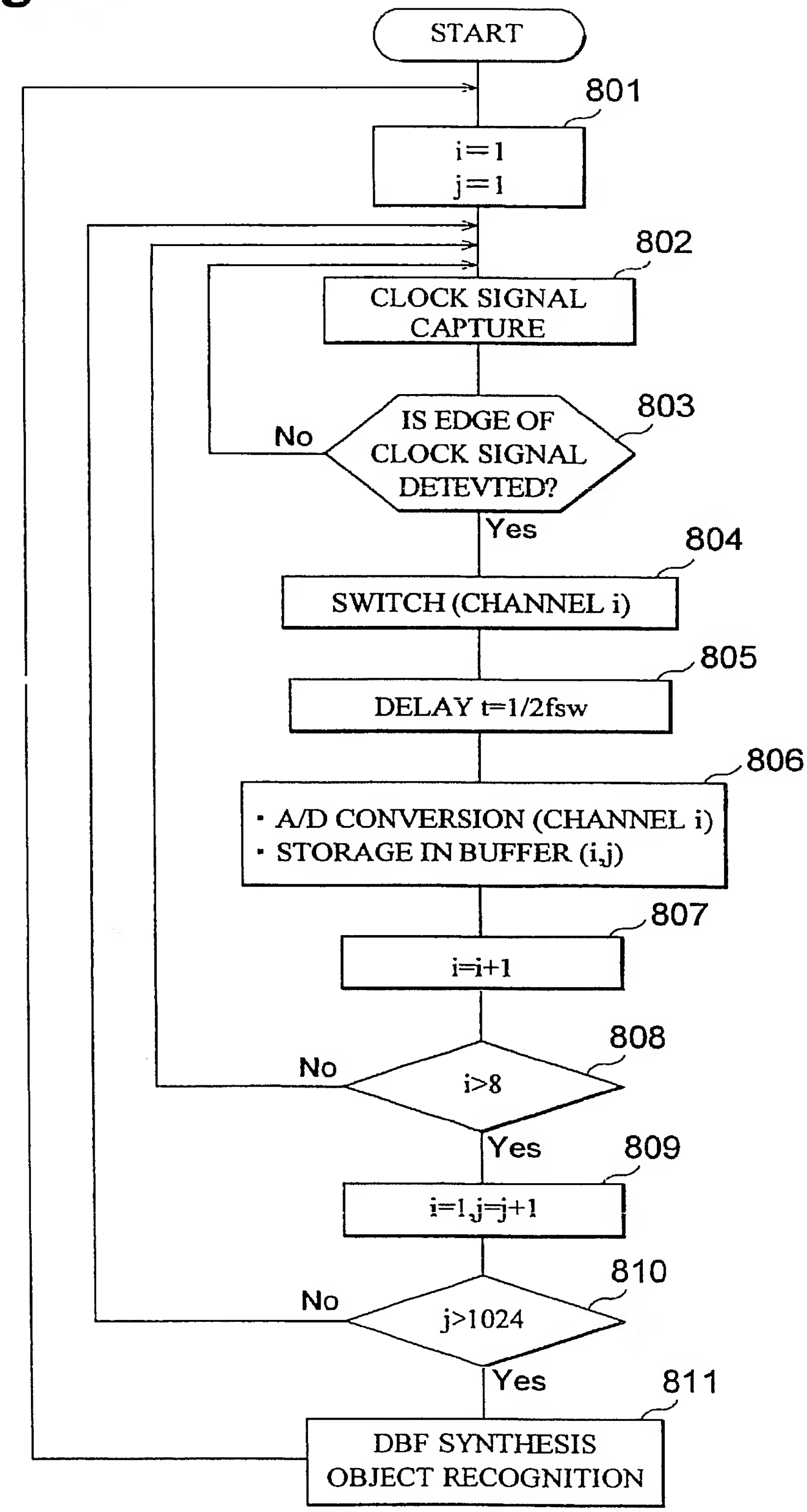


Fig.8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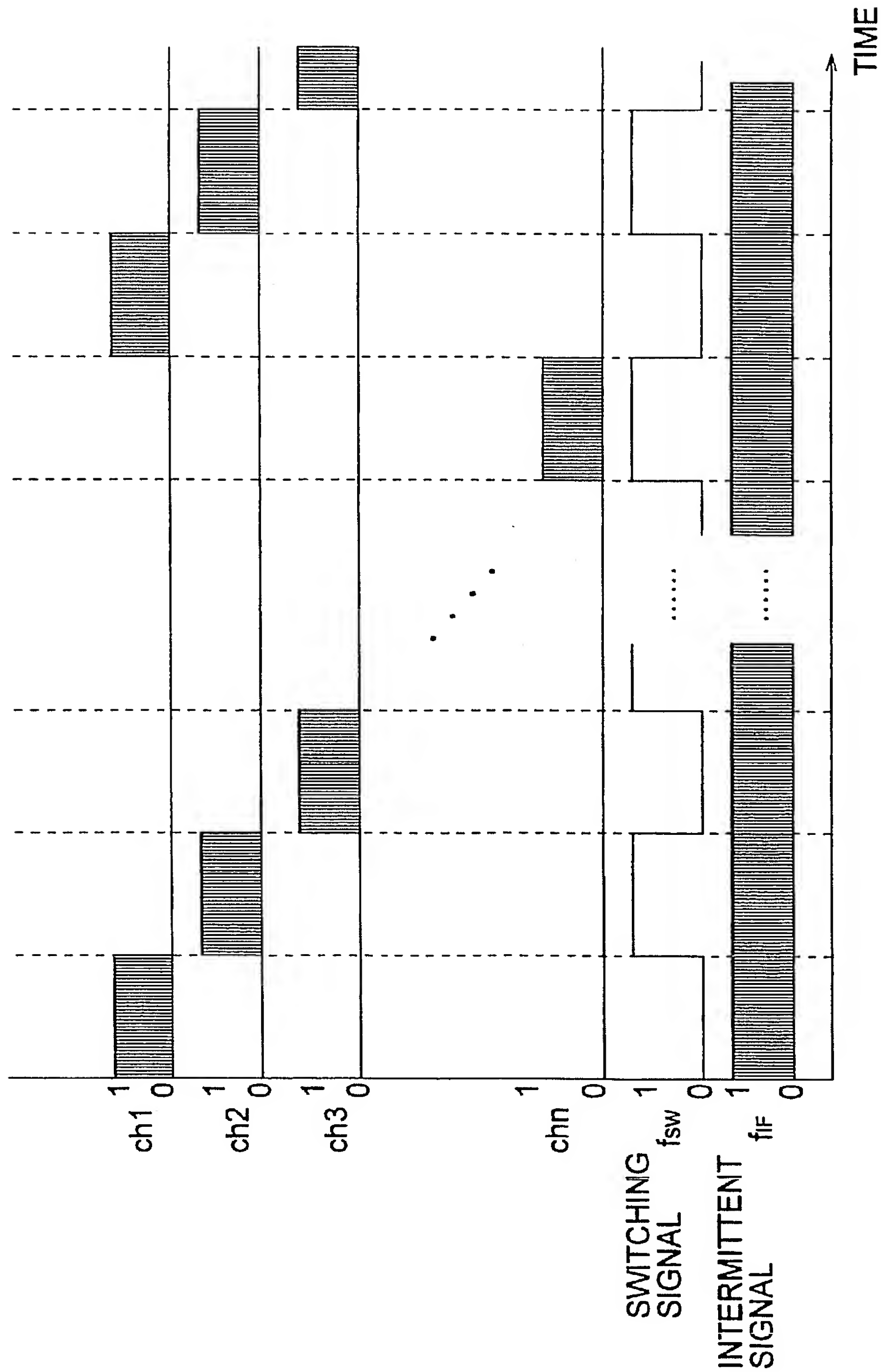
j=1
802
CLOCK SIGNAL CAPTURE
803
IS EDGE OF CLOCK SIGNAL DETEVTED?
No
Yes
804
SWITCH (CHANNEL i)
805
DELAY t=1/2fsw
806
· A/D CONVERSION (CHANNEL i)
· STORAGE IN BUFFER (i,j)
807
i=i+1
808
i>8
No
Yes
809
i=1,j=j+1
810
j>1024
No
Yes
811
DBF SYNTHESIS
OBJECT RECOGNITION

Fig.10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ch2
ch3
chn
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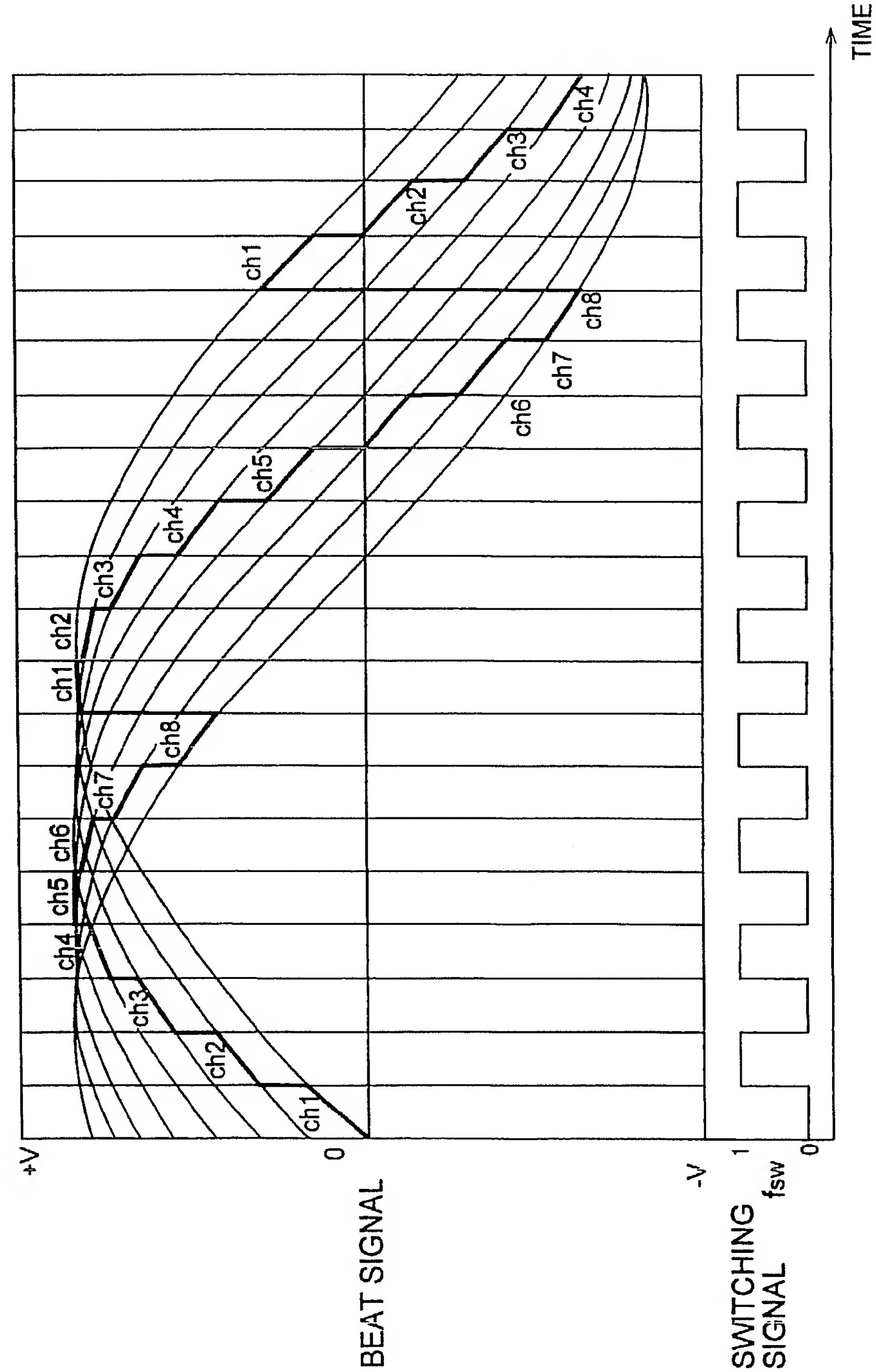
fSW
INTERMITTENT SIGNAL
fIF
1
0
TIME

Fig.12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-V
SWITCHING SIGNAL
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0
TIME
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ch8